

Probing top anomalous couplings at the LHC with trilepton signatures in the single top mode

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We investigate trilepton final states to probe top anomalous couplings at the Large Hadron Collider. We focus on events originating from the associated production of a single top quark with a Z -boson, a channel sensitive to several flavor-changing neutral interactions of top and up/charm quarks. In particular, we explore a way to access simultaneously their anomalous couplings to Z -bosons and gluons and derive the discovery potential of trilepton final states to such interactions with 20 fb^{-1} of 8 TeV collisions. We show that effective coupling strengths of $\mathcal{O}(0.1 - 1) \text{ TeV}^{-1}$ can be reached. Equivalently, branching fractions of top quarks into lighter quarks and gluons or Z -bosons can be constrained to be below $\mathcal{O}(0.1 - 1)\%$.

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INTRODUCTION

Since its discovery, the top quark, given its large mass, is generally considered as a sensitive probe to new physics. In particular, its flavor-changing neutral couplings to gluons and Z -bosons gqt and Zqt (with $q = u, c$) vanish at tree-level as consequences of the unbroken QCD gauge symmetry and the Glashow-Iliopoulos-Maiani mechanism. This also guarantees that in the Standard Model, these interactions stay suppressed at higher orders. Deviations from these predictions have therefore been widely searched for at hadron colliders in flavor-changing neutral top decays [1–5] and single top processes [6–9]. Expressed in terms of branching ratios, current constraints are given at the 95% confidence level by $\mathcal{BR}(t \rightarrow ug) < 5.7 \cdot 10^{-3}\%$, $\mathcal{BR}(t \rightarrow cg) < 2.1 \cdot 10^{-2}\%$ and $\mathcal{BR}(t \rightarrow qZ) < 0.21\%$, assuming one single non-vanishing anomalous coupling.

Existing phenomenological analyses [10–15] mostly focus on direct top quark production and, in a smaller extent, on rarer processes and indirect probes. In this work, we concentrate on the associated production of a top quark with a Z -boson. Although monotop signatures related to invisible Z -boson decays can be interesting for new physics searches [16], we focus on final states where both heavy particles decay into charged leptons. On the one hand, this yields a trilepton topology inferring a Standard Model background under good control. On the other hand, this allows us to design an analysis probing at the same time gqt and Zqt interactions, in contrast to standard investigations that are only sensitive to one type of couplings. Since the production rate of a top quark in association with a Z -boson is highly suppressed in the Standard Model, we aim to interpret possible ex-

cesses in trilepton events as hints of large anomalous gqt and Zqt couplings, as predicted by many new physics theories [17].

In order to facilitate the analysis of new physics effects in top anomalous couplings, the relevant interactions are usually described in terms of a minimal set of effective operators independent of the underlying theory [18]. This bottom-up approach is in particular well motivated when new particles are heavy so that they can be integrated out. In this context, limits on new physics can be derived in a model-independent way. To this aim, we analyze, by means of Monte Carlo simulations, trilepton events to be produced at the Large Hadron Collider (LHC).

This work extends a pioneering study focusing on 14 TeV runs of the LHC with respective luminosity of 10 fb^{-1} and 100 fb^{-1} [11]. First, we update the older results according to current LHC settings, *i.e.*, 20 fb^{-1} of proton-proton collisions with a center-of-mass energy of 8 TeV. Next, we make use of a more accurate description of the Standard Model background relying on state-of-the-art Monte Carlo event generation including multiparton matrix-element merging and on a more advanced simulation of the detector response. We then design a better adapted search strategy that we believe to be worthwhile to be tested by the ATLAS and CMS experiments.

EVENT SIMULATION

Single top production in association with a Z -boson can be driven, at tree-level, by two main mechanisms related to the strong and weak sector, respectively. This is illustrated by the two representative Feynman diagrams of Figure 1 where flavor-changing interactions of top and

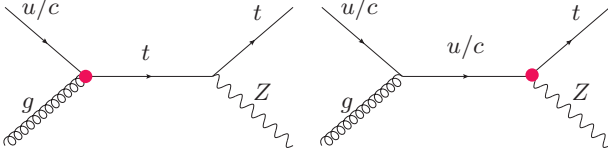


FIG. 1: Representative Feynman diagrams leading to the production of a single top quark in association with a Z -boson. Flavor violation (red dots) occurs either in the strong (left) or weak (right) sector.

light¹ quark fields t and q involve either a gluon (G_μ^a) or a Z -boson (Z_μ). Both cases can be described by means of effective operators to be supplemented to the Standard Model Lagrangian [10, 18, 19]. Denoting the fundamental representation matrices of $SU(3)$ by T_a , the strong and weak coupling constants by g_s and g , the cosine of the weak mixing angle by c_W and the Z -boson and gluon field strength tensors by $Z_{\mu\nu}$ and $G_{\mu\nu}^a$, this effective Lagrangian reads

$$\begin{aligned} \mathcal{L} = & \sum_{q=u,c} \left[\sqrt{2}g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f_q^L P_L + f_q^R P_R) q G_{\mu\nu}^a \right. \\ & + \frac{g}{\sqrt{2}c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (\hat{f}_q^L P_L + \hat{f}_q^R P_R) q Z_{\mu\nu} \\ & \left. + \frac{g}{4c_W} \frac{\zeta_{zqt}}{\Lambda} \bar{t} \gamma^\mu (\tilde{f}_q^L P_L + \tilde{f}_q^R P_R) q Z_\mu \right] + \text{h.c.} . \end{aligned} \quad (1)$$

In this expression, P_L and P_R are chirality projectors acting on spin space and $\sigma^{\mu\nu} = \frac{i}{4}[\gamma^\mu, \gamma^\nu]$. While other operators are in principle possible, they can always be re-expressed in terms of those included in Eq. (1) so that we only consider the minimal set of independent Lagrangian terms above. The magnitude of new physics effects that are assumed to appear at an energy scale Λ are modeled through real dimensionless parameters κ_{gqt} , κ_{zqt} and ζ_{zqt} together with complex chiral parameters $f_q^{L,R}$, $\hat{f}_q^{L,R}$ and $\tilde{f}_q^{L,R}$ normalized to $|f_q^L|^2 + |f_q^R|^2 = |\hat{f}_q^L|^2 + |\hat{f}_q^R|^2 = |\tilde{f}_q^L|^2 + |\tilde{f}_q^R|^2 = 1$.

In this work, we perform a phenomenological analysis based on Monte Carlo simulations of collisions produced at the LHC, running at a center-of-mass energy of $\sqrt{s} = 8$ TeV and for an integrated luminosity of 20 fb^{-1} . For both signal and background, we use the MADGRAPH 5 [20] package for the generation of hard scattering matrix elements including up to two additional jets and convolved with the leading order set of the CTEQ6 parton density fit [21]. Parton-level events produced in this way are then matched to parton showering and hadronization by means of the program PYTHIA 6 [22] and merged according to the k_T -MLM scheme [23, 24].

Detector effects are subsequently accounted for using a modified version of DELPHES 2.0 [25]. The latter includes a modeling of the performances of the CMS detector as described in Ref. [26] and a more recent description of the b -tagging efficiency and mistagging rates. For the latter, we base our implementation on the TCHEL algorithm [27, 28], which leads, *e.g.*, to a $\sim 75\%$ tagging efficiency and a $10-15\%$ mistagging rate for jets with a transverse momentum of $50-80$ GeV. After employing the FASTJET package [29] for jet reconstruction with an anti- k_t algorithm of radius parameter set to $R = 0.4$, simulated events are analyzed within the MADANALYSIS 5 framework [30].

In order to allow for signal simulation, we have implemented the effective Lagrangian of Eq. (1) within the FEYNRULES package [31–35] and subsequently exported the model to a UFO module [36] that has been linked to MADGRAPH 5. We then generate events describing the production of a top (anti)quark decaying leptonically (together with a b -jet and missing energy), in association with a pair of same flavor leptons with opposite electric charges² whose the invariant mass is greater than 12 GeV. In contrast to the diagrams of Figure 1, virtual photon and off-shell Z -boson effects are included in the simulation.

In our study, we investigate simplified scenarios with $f_q^L = \hat{f}_q^L = \tilde{f}_q^L = 0$ and $f_q^R = \hat{f}_q^R = \tilde{f}_q^R = 1$. Leading order inclusive cross sections $\sigma_{tZ}(x)$ read, assuming a single non-vanishing anomalous coupling x at a time,

$$\begin{aligned} \sigma_{tZ}(\kappa_{gut}/\Lambda) &= 8.678 \cdot 10^7 \left| \kappa_{gut} (1\text{GeV})/\Lambda \right|^2 \text{ pb} , \\ \sigma_{tZ}(\kappa_{gct}/\Lambda) &= 3.255 \cdot 10^6 \left| \kappa_{gct} (1\text{GeV})/\Lambda \right|^2 \text{ pb} , \\ \sigma_{tZ}(\kappa_{zut}/\Lambda) &= 5.769 \cdot 10^6 \left| \kappa_{zut} (1\text{GeV})/\Lambda \right|^2 \text{ pb} , \\ \sigma_{tZ}(\kappa_{zct}/\Lambda) &= 2.729 \cdot 10^5 \left| \kappa_{zct} (1\text{GeV})/\Lambda \right|^2 \text{ pb} , \\ \sigma_{tZ}(\zeta_{zut}/\Lambda) &= 2.727 \cdot 10^1 \left| \zeta_{zut} (1\text{GeV})/\Lambda \right|^2 \text{ pb} , \\ \sigma_{tZ}(\zeta_{zct}/\Lambda) &= 1.533 \left| \zeta_{zct} (1\text{GeV})/\Lambda \right|^2 \text{ pb} . \end{aligned} \quad (2)$$

Those predictions agree with the results of Ref. [37] and motivate us to neglect possible effects of the ζ_{zqt} parameters that lead to significantly lower cross sections, not reachable within 2012 LHC data, for anomalous couplings of $\mathcal{O}(0.1-1) \text{ TeV}^{-1}$. In addition, we also consider that strong (κ_{gqt}) and weak (κ_{zqt}) contributions can be treated independently and we include next-to-leading order (NLO) K -factors fixed to 1.3 [14].

We now turn to the simulation of the Standard Model background. First, we do not consider multijet events since their correct treatment requires data-driven methods. We instead rely on existing experimental analy-

¹ The naming light quark (jet) also refers to charmed objects.

² By the terminology *leptons*, we equivalently denote electrons, muons and taus decaying leptonically.

ses that have shown that they contribute negligibly after a selection based on the trilepton topology and missing energy requirements [38, 39]. Events originating from the production of a single gauge boson, decaying leptonically or invisibly, together with jets have been normalized to the next-to-next-to-leading order (NNLO), using total rates of 35678 pb and 10319 pb for W - and Z -boson production calculated by means of the FEWZ program [40, 41] with the CT10 parton densities [42]. Inclusive top-antitop events have been normalized to 255.8 pb, as predicted by the HATHOR package [43] after convolving all NLO diagrams and genuine NNLO contributions with the CT10 parton densities. Single top event generation has been split into the production of three inclusive samples, normalized, at an approximate NNLO accuracy, to 87.2 pb, 22.2 pb and 5.5 pb for the t , tW and s channels [44]. Diboson event weights have been rescaled according to NLO predictions of 30.2 pb, 11.8 pb and 4.5 pb for the WW , WZ and ZZ modes, respectively, as computed by means of the MCFM program [45–47], employing again CT10 densities and after neglecting full hadronic decay modes. Finally, ttV (with $V = W, Z$) events have been normalized to NLO as predicted by MCFM while other simulated rare Standard Model processes rely on MADGRAPH 5 leading-order results. Inclusive cross sections for the ttW , ttZ , tZj , $ttWW$ and $tttt$ channels have been found to be 0.25 pb, 0.21 pb, 46 fb, 13 fb and 0.7 fb, respectively.

ANOMALOUS TOP COUPLINGS AT THE LHC

Events are preselected by requiring exactly three isolated charged leptons (electrons or muons) with a transverse momentum $p_T \geq 20$ GeV and a pseudorapidity $|\eta| \leq 2.5$, using the CMS coordinate system presented, *e.g.*, in Ref. [26]. Lepton isolation is enforced by optimizing, independently for electrons and muons, an isolation variable I_{rel} so that the analysis sensitivity to top anomalous couplings is maximized, the sensitivity being defined as the significance $S/\sqrt{S+B}$ where S and B are respectively the number of signal and background events after all selections. The quantity I_{rel} is derived from the amount of transverse energy, evaluated relatively to the lepton p_T , present in a cone of radius $R = \sqrt{\Delta\varphi^2 + \Delta\eta^2} = 0.3$ centered on the lepton, φ being the azimuthal angle with respect to the beam direction. The selected electrons and muons are asked to satisfy the constraint $I_{\text{rel}} < 0.28$ and $I_{\text{rel}} < 0.06$, respectively.

Two leptons, labeled by ℓ_1 and ℓ_2 , are tagged as originating from a Z -boson decay by selecting the pair of same flavor leptons with opposite electric charges whose the invariant mass $m_{\ell_1\ell_2}$ is the closest to the Z -boson mass m_Z . We further reject events for which $|m_{\ell_1\ell_2} - m_Z| \geq 15$ GeV.

The third lepton ℓ_3 is assumed to originate from a leptonically decaying top quark, being thus accompanied by

TABLE I: Number of expected events for 20 fb^{-1} of LHC collisions at $\sqrt{s} = 8$ TeV, together with the associated statistical uncertainties, after each of the selections described in the text. Two representative signal scenarios have been considered, with non-vanishing κ_{gut} (second column) and κ_{zut} (third column) parameters, respectively, after enforcing a signal normalization of 10 fb. The sum over all background contributions is also indicated (last column).

Selection	$\kappa_{gut} \neq 0$	$\kappa_{zut} \neq 0$	Background
Trilepton topology	41.3 ± 0.3	36.6 ± 0.3	3648.3 ± 143.1
$m_{\ell_1\ell_2} \in [75, 105]$ GeV	38.1 ± 0.3	34.0 ± 0.3	3271.8 ± 136.0
$\cancel{E}_T \geq 30$ GeV	31.8 ± 0.2	26.9 ± 0.3	1362.9 ± 31.9
$m_T^W \geq 10$ GeV	29.6 ± 0.2	25.4 ± 0.2	1256.9 ± 18.8
At least one jet	25.2 ± 0.2	22.4 ± 0.2	549.0 ± 18.5
One single b -tagged jet	17.4 ± 0.2	14.7 ± 0.2	102.8 ± 2.3
$m_t^{(\text{reco})} \leq 250$ GeV	16.4 ± 0.2	13.8 ± 0.2	55.2 ± 1.9

a neutrino yielding missing transverse energy \cancel{E}_T and by a jet issued from the hadronization of a b -quark. We therefore select events with $\cancel{E}_T \geq 30$ GeV and require the reconstructed W -boson transverse mass m_T^W (as defined, *e.g.*, in Ref. [5]) to fulfill $m_T^W \geq 10$ GeV. In addition, we focus on events containing at least one jet satisfying $p_T \geq 30$ GeV and $|\eta| \leq 2.5$ and exactly one b -tagged jet. For all jets, the ratio between the hadronic and electromagnetic calorimeter deposits is also required to be larger than 30%. Finally, the four-momentum of the W -boson from which the missing energy and the lepton ℓ_3 are issued is reconstructed, using the W -boson mass as a constraint. The top quark mass $m_t^{(\text{reco})}$ can then be determined by computing the invariant mass of the W -boson and the b -tagged jet system, and further employed for background rejection. The reconstructed top mass is asked to fulfill $m_t^{(\text{reco})} \leq 250$ GeV, this criterion being found to maximize the analysis sensitivity to new physics.

The number of events surviving each of the selection criteria is indicated, together with the associated statistical uncertainties, in Table I for both the Standard Model background and two representative signal scenarios for which the only non-vanishing anomalous coupling is respectively κ_{gut} and κ_{zut} . After all selections, 34.8 ± 0.7 diboson, 19.0 ± 1.8 $t\bar{t}$ and 1.3 ± 0.1 tZj events remain, all other background contributions being negligible. In comparison, 16.4 ± 0.2 and 13.8 ± 0.2 events are expected for the two signal scenarios after normalizing both samples to a cross section of 10 fb, the difference being due to a different acceptance.

The effect of the top reconstruction is illustrated on Figure 2. After applying the selection strategy described above but the last step, we first present the $m_t^{(\text{reco})}$ spectrum in the Standard Model. The predictions show a broad peaky distribution, with a maximum close to the top mass. We then superimpose two representative sig-

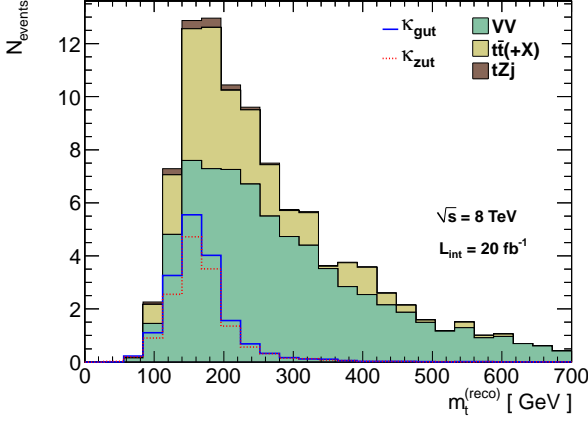


FIG. 2: Distribution of the reconstructed top mass $m_t^{(\text{reco})}$ after the selection strategy described in the text, with the exception of the final cut, for 20 fb^{-1} of LHC collisions at $\sqrt{s} = 8 \text{ TeV}$. We indicate the dominant diboson (VV), top-antitop pair with possibly one or several gauge bosons ($tt(+X)$) and tZj contributions to the Standard Model background, as well as two signal spectra for two representative new physics scenarios, normalized to 10 fb .

nal distributions, normalized to 10 fb . They all present narrower peaks, the distribution maximum being at the top mass. Confronting the shapes of the two signal spectra also indicates that observing tZ trilepton events does not provide any discriminating power among weak and strong flavor-changing neutral top interactions.

The sensitivity of the 2012 LHC run to the four top anomalous couplings under consideration, defined as $S/\sqrt{S+B}$ (see above), is presented for several choices of the κ/Λ parameters in Figure 3 in the case we assume a single non-vanishing coupling at a time. The results are subsequently fitted by polynomial functions so that 3σ and 5σ discovery ranges are extracted. Hence, anomalous couplings such as

$$\begin{aligned} \kappa_{gut}/\Lambda &\geq 0.12 \text{ TeV}^{-1} \text{ (0.09 TeV}^{-1}\text{)}, \\ \kappa_{gct}/\Lambda &\geq 0.42 \text{ TeV}^{-1} \text{ (0.31 TeV}^{-1}\text{)}, \\ \kappa_{zut}/\Lambda &\geq 0.56 \text{ TeV}^{-1} \text{ (0.40 TeV}^{-1}\text{)}, \\ \kappa_{zct}/\Lambda &\geq 1.78 \text{ TeV}^{-1} \text{ (1.30 TeV}^{-1}\text{)}, \end{aligned} \quad (3)$$

can be reached at the 5σ (3σ) level with 20 fb^{-1} of 8 TeV LHC collisions. Using NNLO results for the decay width of the top quark in the Standard Model [48], the limits can be translated in terms of constraints on the branching fractions of rare top decays,

$$\begin{aligned} \mathcal{BR}(t \rightarrow gu) &\leq 0.47\% \text{ (0.25\%)}, \\ \mathcal{BR}(t \rightarrow gc) &\leq 5.1\% \text{ (2.8\%)}, \\ \mathcal{BR}(t \rightarrow Zu) &\leq 0.39\% \text{ (0.20\%)}, \\ \mathcal{BR}(t \rightarrow Zc) &\leq 3.8\% \text{ (2.1\%)}, \end{aligned} \quad (4)$$

at the 5σ (3σ) levels. The obtained limits on $\mathcal{BR}(t \rightarrow$

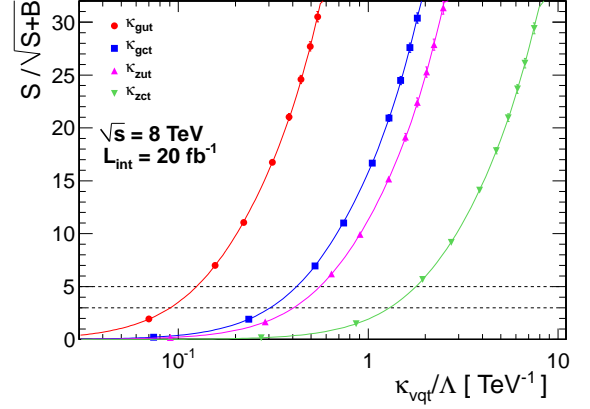


FIG. 3: LHC sensitivity to the considered top anomalous couplings as a function of the interaction strengths, given as $S/\sqrt{S+B}$ after applying the analysis described in the text.

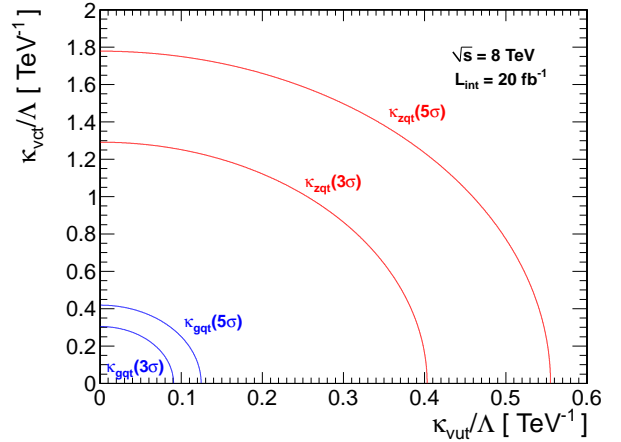


FIG. 4: 3σ and 5σ discovery ranges for top anomalous interactions in the strong (blue, non-zero κ_{gut}/Λ and κ_{gct}/Λ) and weak (red, non-zero κ_{zut}/Λ and κ_{zct}/Λ) sector.

gq/Zc) are found to be not competitive by one or two orders of magnitude with results extracted from direct top production and flavor-changing top decays [5, 9]. In contrast, the bounds obtained on $\mathcal{BR}(t \rightarrow Zu)$ are promising. First, they show that the trilepton analysis which we are proposing can be used to confirm (or possibly improve) the current constraints extracted from flavor-changing top decays in $t\bar{t}$ events at $\sqrt{s} = 7 \text{ TeV}$ [4, 5] by means of an independent measurement at a different center-of-mass energy and with a different integrated luminosity. Next, both channels are statistically independent and thus valuable to be combined for getting stronger bounds on the Ztu coupling strength.

We now allow for several non-zero couplings simultaneously, either in the strong sector (non-vanishing κ_{gut}/Λ and κ_{gct}/Λ parameters) or in the weak sector (non-vanishing κ_{zut}/Λ and κ_{zct}/Λ parameters). In Figure 4,

we extract the associated 3σ and 5σ discovery reaches. We observe a better sensitivity to flavor-changing interactions with an up quark than with a charm quark, as expected from parton densities, the charm content of the proton being suppressed with respect to its up content.

CONCLUSIONS

In this letter, we have investigated the discovery potential of trilepton final states to anomalous, flavor-changing, neutral couplings of the top and light quarks to gluon and Z -boson fields. These interactions induce possibly significant production rates of such final states via the associated production of a leptonically decaying top quark with a dilepton pair. We have designed a search strategy capable to probe simultaneously gqt and Zqt couplings and showed that the 2012 LHC run can reach interaction strengths of order $0.1 - 1 \text{ TeV}^{-1}$. Equivalently, bounds on the associated rare top branching fractions as low as $\mathcal{O}(0.1 - 1)\%$ could be set, possibly improving, in particular, the current limits on the $t \rightarrow Zu$ decay. Our results therefore motivate a further investigation by the ATLAS and CMS collaborations in the context of real LHC data.

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